—研究ノート—
Scientific Note

Monitoring of the Greenland ice sheet using a broadband seismometer network: the GLISN project

Genti Toyokuni[1*], Masaki Kanao[2,3], Yoko Tono[4], Tetsuto Himeno[5], Seiji Tsuboi[4], Dean Childs[6], Kent Anderson[7] and Hiroshi Takenaka[8]

広帯域地震観測網（GLISN）によるグリーンランド氷床モニタリング

豊国源知[1*]・金尾政紀[2,3]・東野陽子[4]・姫野哲人[5]・坪井誠司[4]・
Dean Childs[6]・Kent Anderson[7]・竹中博士[8]

(Received May 2, 2013; Accepted September 19, 2013)

要旨:　グリーンランド氷床は地球規模の気候変動に伴って融解が進行している．近年，氷床融解の過程で末端部の氷河が移動する際に，「氷河地震」と呼ばれる地震動が発生することが知られるようになり，地震観測による氷床モニタリングに関心が集まっている．2009 年に発足した「グリーンランド氷床の地震モニタリング観測網（GLISN）」は，氷床モニタリングを目的として国際共同でグリーンランドや周辺の島々に広帯域地震計を展開するプロジェクトである．日本は GLISN 発足時からの参加国として，2011 年から観測隊を派遣しており，米国と共同で氷床上に観測点 1 点を新設したほか，他の観測点のメンテナンスにも従事している．これらの観測点から得られた長周期地震波形データは，全球地震波伝播モデリングによる理論波形との比較でチェックを行い，設置場所によるノイズの影響が少ない，良質なデータであることを確認した．

[1] 東北大学大学院理学研究科地震・噴火予知研究観測センター．Research Center for Prediction of Earthquakes and Volcanic Eruptions (RCPEVE), Graduate School of Science, Tohoku University, 6–6 Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-8578.
[2] 情報・システム研究機構国立極地研究所．National Institute of Polar Research, Research Organization of Information and Systems, Midoricho 10–3, Tachikawa, Tokyo 190-8518.
[3] 総合研究大学院大学複合科学研究科極域科学専攻．Department of Polar Science, School of Multidisciplinary Sciences, The Graduate University for Advanced Studies (SOKENDAI), Midoricho 10–3, Tachikawa, Tokyo 190-8518.
[4] 海洋研究開発機構．Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 3173–25 Showa-machi, Kanazawa-ku, Yokohama 236-0001.
[5] 成蹊大学理工学部情報科学科．Department of Computer and Information Science, Seikei University, 3–3–1 Kichijoji-Kitamachi, Musashino, Tokyo 180-8633.
[6] IRIS PASSCAL Instrument Center, New Mexico Tech 100 East Road, Socorro, New Mexico 87801.
[7] Incorporated Research Institutions for Seismology (IRIS), 1200 New York Ave., NW, Suite 400, Washington, D.C. 20005.
[8] 岡山大学大学院自然科学研究科地球生命物質科学専攻．Division of Earth, Life, and Molecular Sciences, Graduate School of Natural Science and Technology, Okayama University, 3–1–1 Tsushima-naka, Kita-ku, Okayama 700-8530.
* Corresponding author. E-mail: toyokuni@aob.gp.tohoku.ac.jp

南極資料，Vol. 58，No. 1，1−18，2014
Nankyoku Shiryô (Antarctic Record), Vol. 58, No. 1, 1−18, 2014

Abstract: Global climate change is currently causing melting of the Greenland ice sheet. Recently, a new type of seismic event, referred to as a "glacial earthquake", has been recognized. Such earthquakes are generated by the movements of large masses of ice within the terminal regions of glacier, and represent a new approach for monitoring ice sheet dynamics. In 2009, the multinational GreenLand Ice Sheet monitoring Network (GLISN), a large broadband seismological network in and around Greenland, was initiated to monitor these events. Japan, a partner country of the GLISN project, has been sending a field team to Greenland each year since 2011, when a joint USA and Japanese team first established a dual seismic-GPS station (station code: ICESG-GLS2) on the Greenland ice sheet. In 2012, the same team contributed to the maintenance of ICESG-GLS2, as well as two other stations (NUUK and DY2G-GLS1). The quality of the long-period seismic waveform data obtained by these stations has been checked by comparing the data with global synthetic seismograms. Results indicate that the data from the three stations have not been substantially affected by noise, and that the quality is well controlled.

1. Introduction

The Greenland ice sheet, which covers 80 % of Greenland, is the largest ice body in the Northern Hemisphere. The ice thickness of the ice sheet averages approximately 2 km, and it exceeds 3 km at its thickest point. The dynamics of the ice sheet are such that it influences, and is influenced by, global changes in climate. For example, melting of the entire 2850000 km^3 volume of ice would raise global sea level by 7.2 m (Houghton *et al*., 2001). Therefore, careful monitoring of the Greenland ice sheet will provide important indicators of global climate shifts. Although cryospheric monitoring in Greenland has been conducted using various types of observations, including satellite remote sensing, global positioning systems (GPS), and glaciological and meteorological measurements, the dynamic processes of the ice sheet and outlet glaciers are complex and poorly understood. To investigate and predict the dynamics of the Greenland ice sheet, we contribute a seismic dataset as another fundamentally independent barometer. Rapid climate change over the last decade has increased the need for improved seismic network coverage, increased reliability of locating ice-driven seismic events, and insights into their mechanisms.

The number of seismic events related to glacial movement and ice sheet dynamics has increased in Greenland in recent years; these events include ice quakes, glacial earthquakes, calving events, and glacial rumblings. Glacial earthquakes are representative of such cryo-seismic phenomena; they occur mainly at the edge of the ice sheet, their surface-wave magnitudes are approximately 5, and they are characterized by an absence of high-frequency signals, as compared with standard tectonic earthquakes with similar magnitudes. Ekström *et al*. (2003) discovered this new class of earthquakes and suggested that these events could be excited by large and sudden sliding motions of glaciers, as the radiation patterns show a better fit with landslide mechanisms than with standard faulting mechanisms. Ekström *et al*. (2006) further detected strong seasonality in the patterns of Greenland glacial earthquakes, with fewer events during the winter. Consequently, they proposed that such events are induced by summer surface melting followed by transport of meltwater to the base of the glacier. The frequency of glacial earthquake events on the Greenland ice sheet has doubled over the past 5 years, which is considered to be a dynamic response of the ice sheet to recent climate change.

In addition to an increase in frequency of glacial earthquakes, it has been suggested that the frequency of crustal seismicity in Greenland is also increasing on account of the melting and withdrawal of the ice sheet. However, because the seismic infrastructure in Greenland had long been concentrated along the coastline for practical reasons, the network geometry and station density was insufficient for detecting background seismicity and weak seismic signals related to ice-sheet dynamics.

In 2009, the GreenLand Ice Sheet monitoring Network (GLISN) was initiated as an international project to monitor changes in the ice sheet by deploying a large broadband seismological network in and around Greenland (Dahl-Jensen *et al.*, 2010). The Japanese GLISN committee has been sending an expedition team to Greenland every year since 2011. The first part of this paper consists of a report on the field activities of the Japanese GLISN team for the years 2011–2012. In the second part, we offer the first insight into the data obtained from the stations, and check its accuracy based on comparisons with global synthetic seismograms.

2. The GLISN project

The GLISN project is managed through joint collaboration by institutions in 10 countries: Canada, Denmark, France, Germany, Italy, Japan, Norway, Poland, Switzerland, and the USA. The partner institutions in each country are shown in Table 1. The purpose of the GLISN project is to develop and integrate 27 seismic stations (18 in Greenland and 9 nearby; see Fig. 1a) into a new, real-time, quality-controlled, open-source data repository

Table 1. Partner institutions of the GLISN project.

Country	Institution
Canada	Natural Resources Canada (NRCan)
Denmark	Geological Survey of Denmark and Greenland (GEUS)
France	GEOSCOPE Observatory
Germany	GEOFON Program, Helmholtz-Centre Potsdam, German Research Centre for Geosciences (Deutsches GeoForschungsZentrum, GFZ)
Italy	Istituto Nazionale di Geofisica e Vulcanologia (INGV)
Japan	Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
	National Institute of Polar Research (NIPR)
Norway	Norwegian Seismic Array (NORSAR)
Poland	Institute of Geophysics, Polish Academy of Sciences (IGFPAS)
Switzerland	Swiss Seismological Service (SED), Swiss Federal Institute of Technology Zurich (Eidgenössische Technische Hochschule Zürich, ETHZ)
USA	Incorporated Research Institutions for Seismology (IRIS)
	IRIS Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center
	Lamont-Doherty Earth Observatory (LDEO), Columbia University

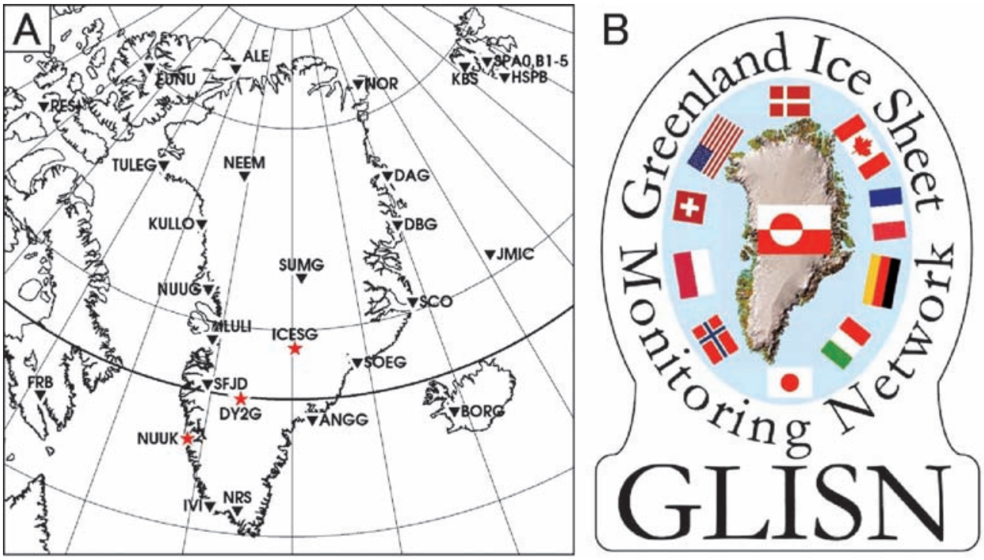

Fig. 1. (a) Location map of the GLISN stations. Stars indicate stations visited by the Japanese team. Triangles indicate the remaining GLISN stations. (b) The GLISN logo.

that is easily accessible via the Data Management Center (DMC), a branch of the Incorporated Research Institutions for Seismology (IRIS), USA.

The GLISN operational objectives are to:

1) upgrade equipment and add real-time telemetry to existing seismic infrastructure in Greenland,
2) install new, telemetered, broadband seismic stations on Greenland's coastline and the ice sheet,
3) integrate telemetry from existing real-time, high-quality, broadband stations in and around Greenland into the GLISN network, and
4) distribute the archived data to users and international data centers.

Most of the funding for the GLISN has been provided by a 3-year grant (ending in 2012) from the National Science Foundation (NSF), USA (award #0922983). This grant has made it possible to install six new stations and upgrade five existing stations operated by the Geological Survey of Denmark and Greenland (GEUS) (Table 1) to meet the technical standards for equipment and installation as planned by the GLISN.

Site reconnaissance and inspection of some existing GEUS seismic stations in Greenland was conducted for one week in 2009 by two researchers, Kent Anderson and Guy Tytgat of IRIS. In 2010, field efforts focused on deploying two new seismic stations, Daneborg (station code: DBG) and Nuuk (NUUK), and upgrading five existing GEUS stations: Thule Air Base (TULEG), Station Nord (NOR), Narsarsuaq (NRS), Tasiilaq (ANGG), and Ittoqqortoormiit (SCO). In 2011, the GLISN team's primary focus was the deployment of seismic stations at three inland ice sites: DYE-2, Raven Camp (DY2G-GLS1), NEEM Drilling Camp (NEEM-GLS3), and Ice South Station (ICESG-GLS2). A station was also installed on the coast of East Greenland at Sødalen (SOEG). In 2012, field activity was devoted to final checks for commissioning of the GLISN network, and completion of all field work that had been delayed in preceding years.

Japan is a partner country from when the GLISN project was launched in 2009. Two authors of this paper, Seiji Tsuboi and Masaki Kanao, are GLISN steering committee members, and three authors, Yoko Tono, Tetsuto Himeno, and Genti Toyokuni, are also members of the Japanese team. The Japanese GLISN team has been participating in the GLISN field operation since 2011. In 2011, the team installed the seismic-GPS station ICESG-GLS2. As it is a joint station maintained by the USA and Japan, the National Institute of Polar Research (NIPR), Japan, has contributed a seismometer and a data logger, while all other instruments, the overall design of the station, and members for the main field support are provided by IRIS Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) Polar Group, USA, whose primary mission is to support seismic monitoring experiments in Arctic and Antarctic regions. In 2012, we serviced three stations (ICESG-GLS2, NUUK, and DY2G-GLS1) in cooperation with IRIS/PASSCAL colleagues; these stations are shown in red in Fig. 1a. Activities of the Japanese GLISN team are supported by a Japan Society for the Promotion of Science (JSPS) Grant in Aid for Scientific Research (KAKENHI 24403006).

3. Observation base at Greenland

Greenland is an autonomous country within the Kingdom of Denmark. There are no direct flights to Greenland from Japan, and most flights are routed through Copenhagen, Denmark, or Reykjavík, Iceland. However, only the flight via Copenhagen lands at Kangerlussuaq, western Greenland, which is the location of the international base for scientists, named Kangerlussuaq International Science Support (KISS). The KISS building is owned and operated by the Greenland Airport Authority (Grønlands Lufthavnsvæsen, GLV). Most of the logistical support required for observations in Greenland (*e.g.*, cargo, equipment, contracts with airlines for flights to observation points) is managed by CH2M HILL Polar Services (CPS), which rents office space and warehouses in the KISS building and provides arctic logistics for NSF-funded researchers. Scientists can rent the guest room at KISS for DKK 300 per day, and can prepare equipment and test instruments in the warehouses. Camping and expedition equipment is also available for rent there.

4. 2011 field operation

Station ICESG-GLS2 located at 69°5′32″N, 39°38′51″W at an elevation of 2930 m, is on a ridge of the Greenland ice sheet approximately 400 km south of its summit point. The station, which is in an isolated location, contains both seismic (ICESG, ICES refers to Ice South, G refers to GLISN) and GPS (GLS2) stations. For rapid surface deployment, a de Havilland Canada DHC-6 (Twin Otter), owned and operated by Norlandair (Akureyri, Iceland), was chartered for flights between Kangerlussuaq and ICESG-GLS2. During the install operation, the Twin Otter made five shuttle flights to ferry team members, camping gear, station hardware, and instruments (total load: 3378 kg; upper load limit per flight: 680 kg). Participating members were Dean Childs, Robert Greschke, Masaki Kanao, Yoko

Tono, Genti Toyokuni, Karl Eiríksson, and Jóhann Jónsson (Table 2). The total observation period of the Japanese team was 11 days (Jun. 2–12, 2011). The schedule for the 2011 field operation is summarized in Table 3.

Details of the instruments installed at station ICESG-GLS2 are as follows. The seismometer is a Cold Rated Güralp CMG-3T (flat response to ground velocity between 120 s and 100 Hz). The data are collected using a Quanterra Q330 digitizer and a Quanterra Baler44 data logger. The Cold Rated CMG-3T is designed to operate at temperatures down to −55℃. Generally, seismometers endure continuous operation at low temperatures if startup has been achieved; the heat dissipated by the feedback and control electronics helps establish a stable operating environment. Problem is the startup procedure, as the lubrication in the mass centering and mass locking assemblies solidifies during transportation and storage in extremely cold environment. The Cold Rated CMG-3T unit,

Table 2. List of participants of the 2011–2012 field operations.

Team	Name	Affiliation
Japan	Himeno, Tetsuto	NIPR
	Kanao, Masaki	NIPR
	Tono, Yoko	JAMSTEC
	Toyokuni, Genti	NIPR (2011), Tohoku Univ. (2012)
USA	Childs, Dean	IRIS/PASSCAL
	Greschke, Robert	IRIS/PASSCAL
	Hebert, Jason	IRIS/PASSCAL
	Young, Kathy	CPS
Pilots	Eiríksson, Karl	Norlandair
	Gunnarsson, Kristinn Elvar	Norlandair
	Jóhannsson, Davíð Smári	Norlandair
	Jónsson, Jóhann	Norlandair

Table 3. Schedule summary of the 2011 field operation.

Date	Activity
Jun. 2	Departure of Japanese team from Narita, Tokyo, to Copenhagen, Denmark.
Jun. 3	Japanese team arrives in Greenland by flight from Copenhagen to Kangerlussuaq.
Jun. 6–8	Installation of station ICESG-GLS2 (Dean Childs, Robert Greschke for three days; Japanese team participated in a day trip on Jun. 7). Use the Norlandair Twin Otter flight.
Jun. 10	Japanese team leaves Greenland to Copenhagen.
Jun. 12	Japanese team arrives in Japan.

however, is constructed with insulated motors and upgraded assemblies for the low-temperature operation. Other differences between Cold Rated and conventional CMG-3T units include:

1) all Cold Rated CMG-3Ts are cold-start tested at −55℃,
2) specialized O-ring assemblies are used on the sensors that seal the sensor casings,
3) output voltage is reduced to a 4.5 V differential from 10 V to save power consumption, and
4) microswitches, as opposed to current limits, are used to determine whether the sensor mass is locked.

The GPS data are collected at 30 s intervals by a Trimble NetR9 GNSS reference receiver. State of health (SOH), seismic, and GPS time series data (sampling rate: 125 s) are transmitted by two Xeos XI-100B global-access remote-control modems, utilizing the Iridium satellite network.

Nine solar panels (Sharp NE-80EJEA, 80 W, 12 V) and 26 6 V AGM batteries provide power to station ICESG-GLS2. All batteries and instruments, except for the seismometer and external antennas, are packed into two insulated high-strength plastic boxes (called “orange boxes”, on account of their color). Figure 2 shows an external view of the station. The recording and power supply systems are shown in Figs. 3 and 4, respectively.

Field operations of the Japanese team at station ICESG-GLS2 included:

1) installation of a seismometer,
2) installation of a GPS antenna,
3) construction of solar power generation systems,
4) loading and internal configuration of the instrument boxes, and

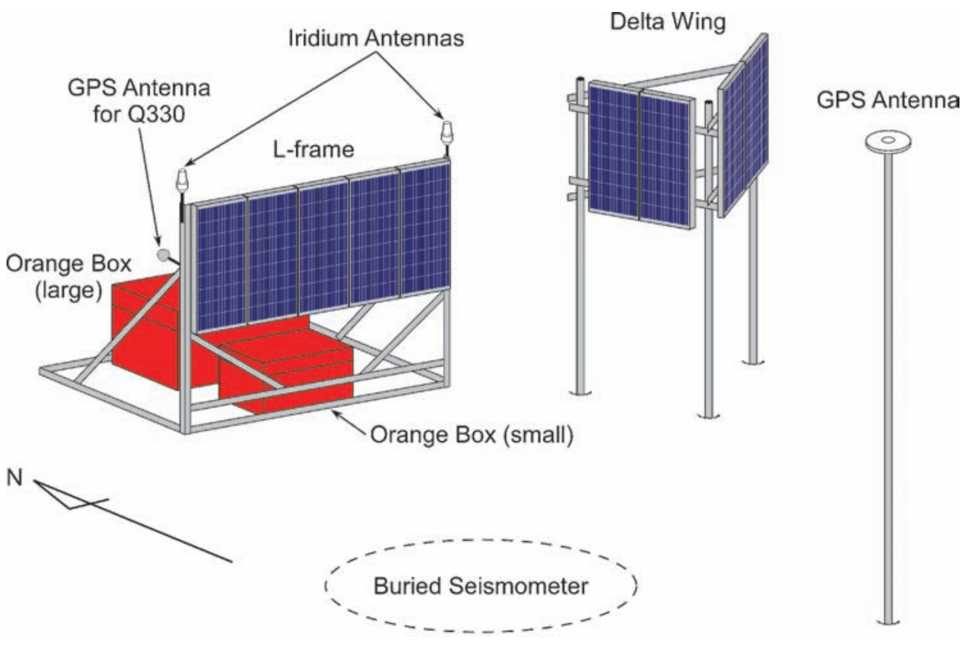

Fig. 2. Schematic view of station ICESG-GLS2.

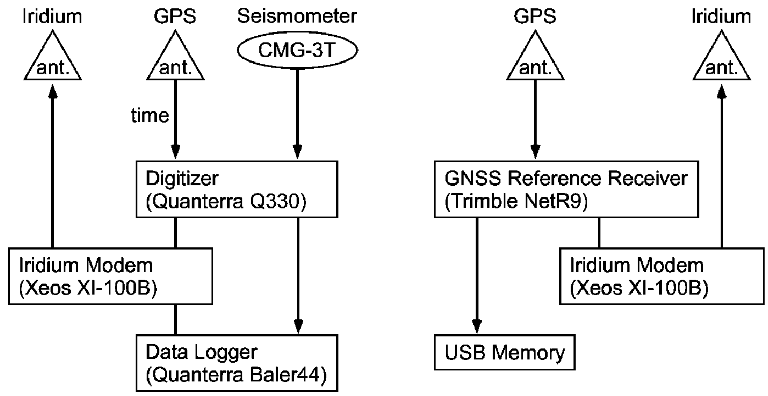

Fig. 3. Recording system at station ICESG-GLS2 in 2011.

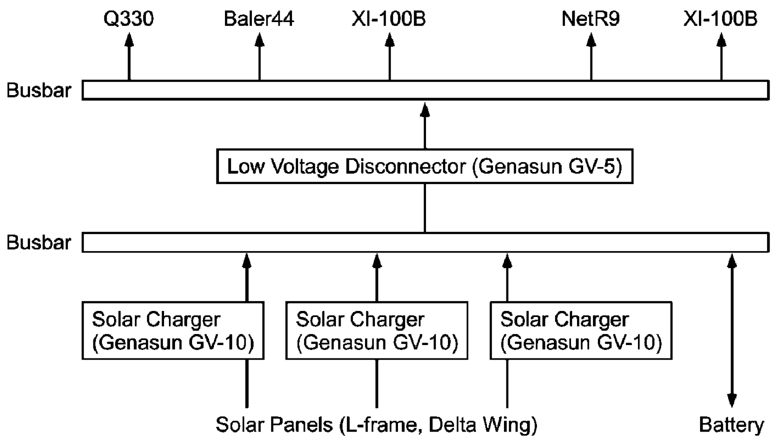

Fig. 4. Power supply system at station ICESG-GLS2 in 2011.

5) final confirmation of instrument health and functionality, and quality of the data acquisition systems.

Installation processes on the ice sheet required a great deal of time and effort for site preparation on the snow. For installation of the seismometer, we first dug a hole in the snow approximately 1.5 m square and 1 m deep, and boot-packed the bottom of the hole. Then, we dug a smaller pit in the bottom of the hole, approximately 50 cm in diameter and 80 cm deep, and embedded a plastic drum in the hole; the seismometer was placed in the drum, and was then leveled. Digging was generally conducted by pairs of team members: one member loosened the snow and ice at the bottom of the hole, and the other member staying out of the hole removed the snow from the hole by a bucket.

The seismometer was oriented to true north by planting a bamboo pole in the snow in a location due south of the seismometer, and laying an aluminum reference bar across the surface of the hole and centered over the seismometer. The bar was then aligned in the direction of the bamboo pole by viewing from directly above the seismometer. Visual alignment of the N—S oriented reference bar (see Fig. 5a) resulted in a placement accuracy of the seismometer of $\pm 1^\circ$ with respect to true north. After placing the seismometer, the lid of the plastic drum was closed, the lower pit containing the drum and seismometer was covered by a plastic dome (radius: 60 cm) (Fig. 5b), and the hole was back-filled with snow. Installation of the seismometer required a total of 2 man hours.

Installation of the Trimble NetR9 receiving GPS antenna (Trimble Zephyr) required digging a hole approximately 1.5 m in diameter and 1.3 m deep. The 4.27 m aluminum antenna pole, which was mounted on a 61×61 cm wooden base, was placed in the hole, aligned to vertical, and then the hole was back-filled with compressed snow; the snow was compressed by boot-packing during filling of the hole. Installation of the GPS pole required 1 man hour.

Two solar panel mounts were installed at station ICESG-GLS2. Five solar panels were mounted on an “L-frame”, which is so-called because it is “L-shaped” when viewed from the side. Four solar panels were mounted on a three-legged frame known as the “Delta Wing”, so-called because two of the panels are oriented towards the SE and two are oriented towards the SW, such that they form a triangle when viewed from above. The Delta Wing is designed to receive sunlight over a wide range of solar angles. The L-frame was anchored by the weight of the two orange instrument/battery boxes, which fit into two rectangular frames (part of the L-frame base design). The Delta Wing was anchored by burying the pole bases in the snow to a depth of 1 m, and guying the structure from the front and back with high-strength 1/8″ stainless steel cable. The cables were anchored with snow anchors, and the wires were tensioned using turnbuckles.

Batteries and instruments are housed in the two orange boxes. The larger box contains 20 batteries and a power board with recording instruments, while the smaller box contains an additional six batteries. External cables (to antennas, solar panels, and sensors) exposed to the elements were covered with heat-insulating materials to prevent damage to the cables. The cables were shallowly buried in the snow, and the buried cable locations and the position of seismic vault were marked with flag less bamboo poles. During installation, temperatures were approximately -5℃ and wind speeds were slight.

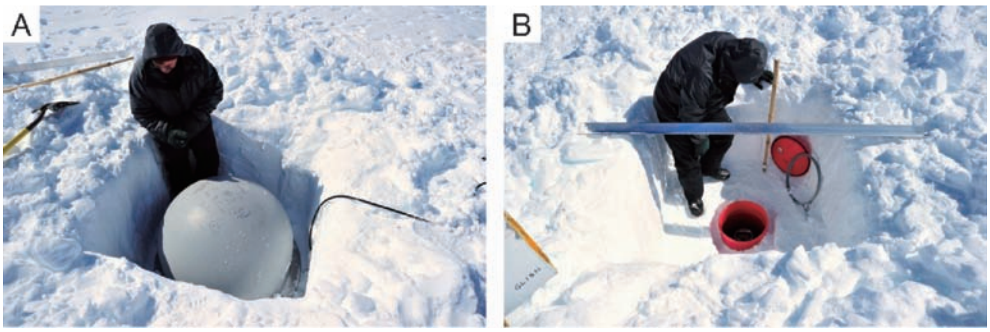

Fig. 5. Photos showing the seismometer deployment at station ICESG-GLS2 in 2011. (a) Adjustment of seismometer direction. (b) Plastic dome covering the seismometer.

5. 2012 field operation

The 2012 field operation of the Japanese team focused on data acquisition and maintenance at three stations: ICESG-GLS2, NUUK, and DY2G-GLS1. Team members included Masaki Kanao, Yoko Tono, Tetsuto Himeno, and Genti Toyokuni (Table 2), and the total observation period 16 days (May 28–Jun. 12, 2012) as summarized in Table 4. Prior to departure, all participants traveling to remote places in Greenland must pass an NSF-mandated physical exam (http://www.polar.ch2m.com/SingleHTMLTextArea.aspx?P=6b1968437b7f41ddb080b87e08789ccc). This year, Genti Toyokuni was physically qualified to remain overnight at station ICESG-GLS2. The operation details are as follows.

5.1. ICESG-GLS2

Field operations were conducted over a 2-day period (May 30–31) by team members Dean Childs, Jason Hebert, Genti Toyokuni, Davíð Smári Jóhannsson, and Kristinn Elvar Gunnarsson (Table 2). All members remained overnight on the ice sheet: pilots slept in the airplane, and all other members slept in individual mountain tents.

To our surprise, snowfall during the previous year exceeded our expectations, and was sufficient to completely cover the L-frame (Fig. 6b). Large snowdrift had developed around the L-frame, as the prevailing wind direction at the site is from the south; it is the direction towards which the solar panels are confronting. On the other hand, large drifts were absent around the Delta Wing, as the mount contains an open space between the snow surface and the solar panels. Snowdrifts on the Delta Wing measured 146 cm, and up to 219 cm on the

Table 4. Schedule summary of the 2012 field operation.

Date	Activity
May 28	Departure of Japanese advance party (Yoko Tono, Tetsuto Himeno, Genti Toyokuni) from Narita, Tokyo, to Copenhagen, Denmark.
May 29	Japanese advance party arrives in Greenland by flight from Copenhagen to Kangerlussuaq.
May 30–31	Maintenance of station ICESG-GLS2 (Dean Childs, Jason Hebert, Genti Toyokuni). Use the Norlandair Twin Otter flight. All participants and pilots stay overnight at the site.
Jun. 1	One member of Japanese team (Yoko Tono) leaves Greenland.
Jun. 4	One member of USA team (Jason Hebert) leaves Greenland.
Jun. 4–6	Maintenance of station NUUK (Dean Childs, Genti Toyokuni). Use commercial flight of the Air Greenland. Stay the GINR guest house.
Jun. 6	One member of Japanese team (Masaki Kanao) arrives in Greenland.
Jun. 7–10	Maintenance of station DY2G-GLS1 (Dean Childs, Kathy Young, Masaki Kanao, Tetsuto Himeno, Genti Toyokuni). Use the 109th Airlift Wing LC-130 flight.
Jun. 11	Japanese team leaves Greenland to Copenhagen.
Jun. 13	Japanese team arrives in Japan.

L-frame.

Maintenance at station ICESG-GLS2 consisted of:

1) digging out the orange boxes to retrieve data (2 man hours) and update instruments,
2) raising height of the solar panels on the Delta Wing by approximately 20 cm (40 man-minutes),

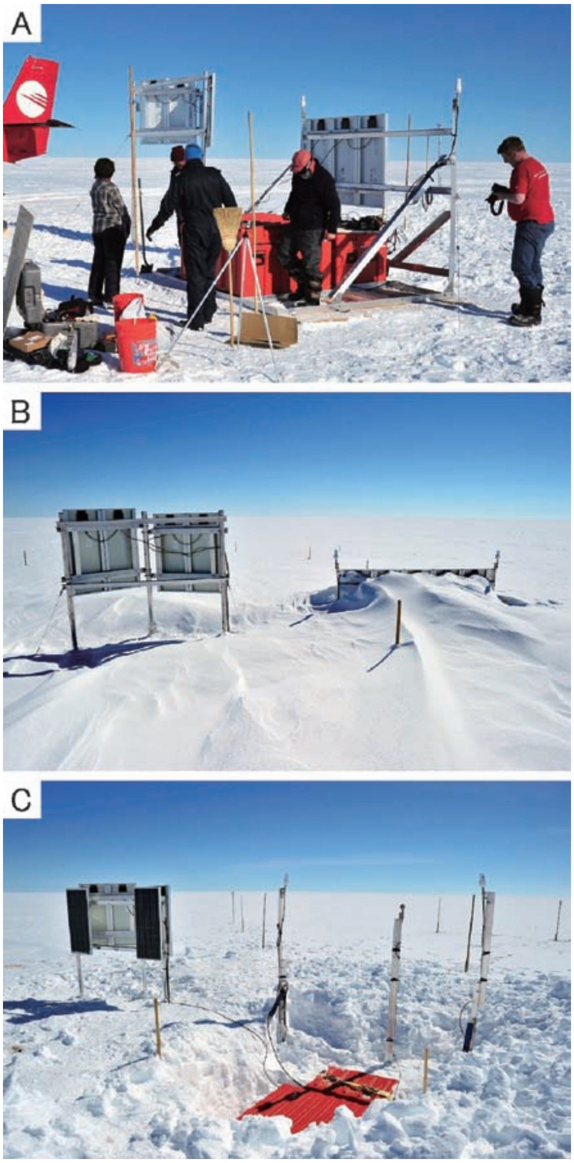

Fig. 6. Photos showing exterior changes at station ICESG-GLS2.
(a) Jun. 7, 2011: the L-frame under construction. (b) May 30, 2012: the L-frame buried under snow. (c) May 31, 2012: five solar panels of the L-frame were removed and two were installed behind the Delta Wing, facing northward.

3) digging out and removing the solar panels on the L-frame, which were buried by snow and were causing snow to drift over the boxes (1 man hour),
4) installing two solar panels on the north side of the Delta Wing (30 man-minutes; see Fig. 6c),
5) raising height of the Xeos and Q330 GPS antennas (2.5 man hours), and
6) conducting a site survey, which included measurements of the distances and azimuths between a reference point and the GPS antenna, bamboo poles, and solar panels (1 man hour).

Figure 7 shows changes in input voltages at station ICESG-GLS2 before and after the 2012 maintenance operation. Before the maintenance, voltage differentials between day and night were large, while after maintenance, voltages were stabilized by installation of northward-oriented solar panels toward.

5.2. NUUK

Station NUUK is located on the southwest coast of Greenland on the outskirts of Nuuk, the capital of Greenland, at 64°11′1.4″N, 51°40′4.6″W, at an elevation of 130 m. Access to Nuuk from Kangerlussuaq is by commercial Air Greenland flights (flight time: $<$1 hour). Although the Nuuk Airport is a technical base for Air Greenland, it is unable to service large planes on account of airway limits related to nearby mountains, and problems with the weather.

Station NUUK, located approximately 800 m SE of the airport facility (Fig. 8a), utilizes a valve house building for the city water supply; the site is on solid rock at the base of the mountain slope (Fig. 8b). The valve house is managed by Nukissiorfiit, a company that supplies energy and water to Greenland end-users.

The valve house is a reinforced concrete structure, with one story above ground and two stories below ground. The main city water line, which is in a bedrock tunnel at the second basement, approximately 10 m below the surface, passes through the building and continues underground to a nearby lake. The lake is the main source of water for the city of Nuuk. A pump forces air from the surface into the tunnel, to provide air circulation in the tunnel during servicing. The first basement of the valve house is used as a storage space for spare materials. An AC power line from another valve house facility, located approximately 400 m to the WNW, supplies power to the building. The power cable between the two buildings, which runs along the surface beside rudimentary road access, is protected by a

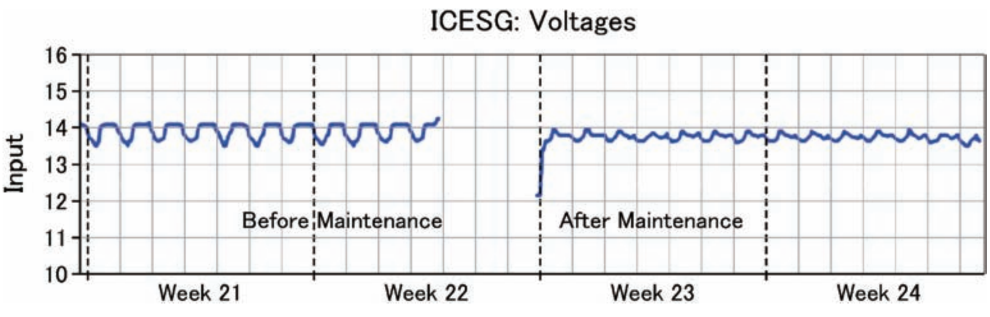

Fig. 7. Input voltage of station ICESG-GLS2 before and after 2012 maintenance.

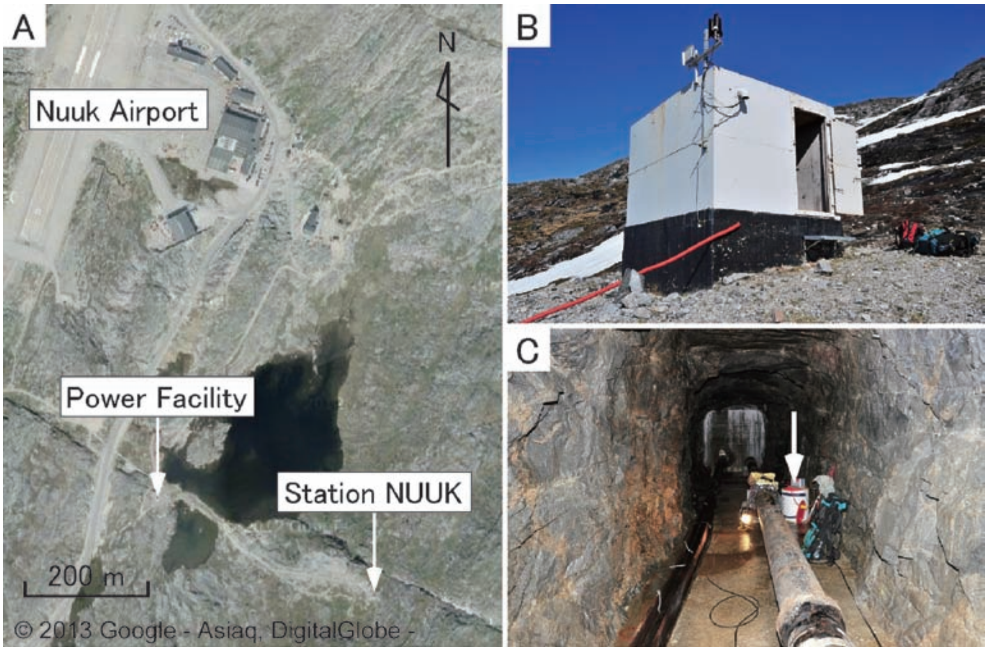

Fig. 8. (a) Map showing the location of the Nuuk Airport, station NUUK, and its power facility. (b) Exterior view of station NUUK. (c) Inside the tunnel at the second basement level. Arrow indicates the location of the STS-2 seismometer.

plastic casing.

A Streckeisen STS-2 seismometer was installed in the pipeline tunnel by the USA GLISN team in 2010 (see Fig. 8c). Most of the instruments, including a digitizer (Quanterra Q330), a data logger (Quanterra Baler44), and four 6 V AGM batteries, are housed on the ground floor of the building. A Forgen wind turbine and a GPS antenna for the Q330 are fixed to the roof.

Field operations at NUUK were conducted over a 3-day period (Jun. 4–6) by Dean Childs and Genti Toyokuni. The following maintenance tasks were performed at station NUUK:

1) data retrieval and updating of instruments,
2) cleaning of battery terminals,
3) independent cross-checking of the building location and azimuths using Google Earth, a Brunton compass, and an iXBlue Octans gyrocompass,
4) checking on the orientation of the seismometer, using the gyrocompass,
5) anchoring of the uphill end of the external AC power cable at the station site to prevent it from sliding downhill, and
6) shipping of a large dome, which had been stored at the site for another project.

The anchoring of the external AC power cable was necessary because the cable migrates downhill on account of gravity; we covered the cable with heavy stones to prevent this. The operations listed above required a total of 7.5 man hours.

While at Nuuk, the team stayed at the Greenland Institute of Natural Resources (GINR) guesthouse. In the GINR building, an Active Earth Monitor (AEM), which is a simple-to-implement and inexpensive terminal providing real-time seismological and other Earth science related information to a wide audience, was installed by IRIS in 2011 as a part of GLISN field activities.

5.3. DY2G-GLS1

Station DY2G-GLS1 is located on the ice sheet just below the Arctic Circle, at 66°28′46.6″N, 46°18′35.9″W, at an elevation of 2120 m. The station is located close to the equilibrium zone on the ice cap, the zone in which the rate of snow melting and ablation is approximately equal to that of accumulation (CH2M HILL Polar Services, 2013). The field operation at DY2G-GLS1, conducted over a 4-day period (Jun. 7–10), included team members Dean Childs, Kathy Young, Masaki Kanao, Tetsuto Himeno, and Genti Toyokuni (Table 2); three nights were spent in tents.

Although stations ICESG-GLS2 and DY2G-GLS1 are both on the ice sheet, the circumstances at each station are quite different. First, station DY2G-GLS1 is near to a camp with an established runway: Raven Camp. Raven Camp is a training facility and refueling depot for the 109th Airlift Wing of the New York Air National Guard (NYANG), which provides heavy airlift support for the NSF's polar research program. The runway at Raven Camp allows transport of all equipment by a Lockheed LC-130, which is a ski-equipped variant of the C-130 Hercules, a four-engine turboprop military transport aircraft. The 109th Airlift Wing, which has flown missions to Greenland since 1975, is the only military unit in the world to fly LC-130 cargo planes. The runway is established by grooming the snow surface with snow machines. Two CPS staff members (currently, Drew Abbott and Silver Williams) live at Raven Camp during the summer season (Apr.–Sep.), and are responsible for daily maintenance of the runway, interaction with pilots through radio and cargo exchange, and support of skiers crossing the ice cap.

A noticeable feature near station DY2G-GLS1 is a deserted DYE-2 radar station, whose name is the origin of station DY2G-GLS1 name. The DYE-2 station was part of the U.S. Air Force Distant Early Warning Line (USAF DEW Line), a series of radar sites established across the Arctic during the cold war for the purpose of detecting Soviet bombers and providing early warning of a sea or land invasion (Walsh and Ueda, 1998). The DYE-2 station was constructed in 1959, but was closed in 1988 because of column and footing tilt of the building. The station code name, DYE, is derived from Cape Dyer, Baffin Island, Canada, which is the location of the DYE-Main station.

Station DY2G-GLS1 is located approximately 2.1 km SSW of the hut at Raven Camp, and snowmobiles are used for transportation between the camp and station. The seismic site at DY2G is twice as large as that at ICESG. Two seismometers are installed at station DY2G: a Güralp CMG-3T is installed as a surface seismometer, and a Güralp CMG-3TB borehole seismometer is deployed in a 300 m borehole.

The borehole was drilled in 2011, in cooperation with the Ice Drilling Design and Operations (IDDO, http://icedrill.org/about/iddo.shtml) program, members of the 2001 Arctic Circle Traverse (ACT), and a crew from CPS. In May 2011, when the station was installed, an engineer from Güralp Systems Ltd., the designer and manufacturer of both seismometers, accompanied the GLISN team to approve and monitor the system prior to final deployment of the borehole seismometer. The DY2G seismic system includes a digitizer (Quanterra Q330), a data logger (Quanterra Baler44), and an Iridium device (Xeos XI-100), and is supported by an L-frame (five solar panels), a Delta Wing (four solar panels), 26 AGM batteries, and a wind generator. The internal devices and batteries are packed into two orange boxes, one large and one small.

The GPS station (GLS1) includes a Zephyr model GPS antenna, a GNSS reference receiver (Trimble NetR9), and an Iridium device (Xeos XI-100). The GPS instruments are independently supported by a second L-frame (four solar panels), 12 AGM batteries, and a wind generator. The internal devices and batteries are packed into one large orange box.

The 2012 operations at station DY2G-GLS1 were conducted in windy and snowy weather. The maximum wind speed reached 20 m/s on the night of June 7. The following maintenance tasks were performed at the site:

1) data retrieval and updating of instruments for the seismic system,
2) removal of two solar panels from the drift-buried seismic L-frame, and reinstallation on the north side of the Delta Wing,
3) removal of the malfunctioning DY2G wind generator,
4) data retrieval, updating of instruments, and addition of two AGM batteries to the GPS station, and
5) winterization of both stations.

These operations required a total of 13.5 man hours. Because the orange boxes and solar panel flames were not deeply buried in the snow, the amount of digging required was minimal.

6. Quality of seismic waveform data

In this section, we provide the first insight into seismic data obtained at station ICESG, and compare these data with data obtained from stations NUUK and DY2G. First, we check waveforms with high frequencies, which carry near-field seismic information. Figure 9 shows three-component seismograms from ICESG and NUUK for the April 11, 2012, Sumatra earthquake; this earthquake (depth: 45.6 km), with a magnitude of $M\mathrm{w} = 8.6$, was the largest earthquake during our observation period. A total of 6000 s of recordings are plotted in Fig. 9 using a band-pass filter with a band width of 1–800 s.

Unlike the results obtained at NUUK, which is installed on underground bedrock, the observations at ICESG would be affected by the thick ice sheet; the low seismic velocity of the ice, and the large velocity contrast at the contact between ice and underlying bedrock, factors which cause large amplifications and waveform distortions. In addition, shallow-buried seismometers in the surface snow tend to be affected by wind-generated noise. Although the amplifications and waveform distortions are removable via waveform modeling, including that of the ice sheet model, contamination by wind noise and installation status can reduce the data quality of the entire network. At present, waveforms from ICESG do not contain large noise at up to high frequencies, which indicates the success of our careful installation at ICESG.

To further check the quality of observations for far-field body waves, we next compare the obtained waveforms with long-period synthetic seismograms. Global synthetic seismograms were generated using the spherical 2.5-D approach, which solves the 3-D

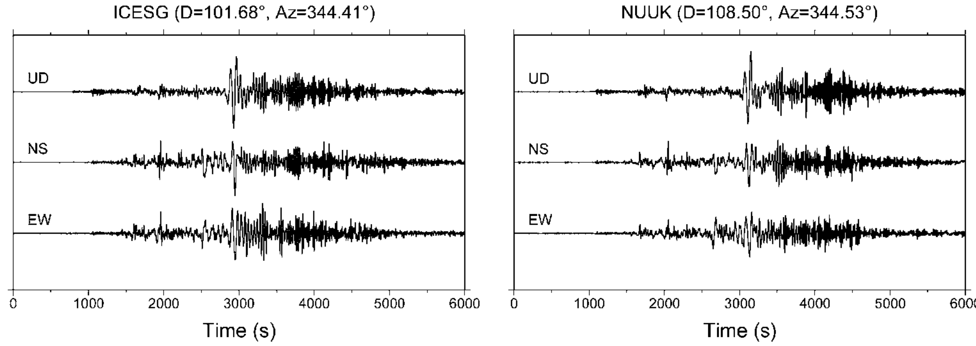

Fig. 9. Observed seismograms for the Apr. 11, 2012, Sumatra earthquake at stations ICESG (left) and NUUK (right). A total of 6000 s seismograms for the vertical, north—south, and east—west channels are shown. All traces are band-pass filtered at 1–800 s.

elastodynamic equation in spherical coordinates on a 2-D cross section of a realistic Earth model (Toyokuni *et al.*, 2012a). This method approximates a structural model as rotationally symmetric along a vertical axis that includes the seismic source, such that the effects of 3-D wave propagation can be correctly modeled using only on a 2-D structural cross-section. The 2.5-D approach saves computational time and memory, as compared with 2-D modeling, but generates 3-D synthetic seismograms that enable direct comparisons between real and synthetic data.

The spherical 2.5-D approach has been used in practical applications since the 1990s, based on finite-difference method (FDM) (*e.g.*, Igel and Weber, 1995, 1996); however, these traditional schemes used only axisymmetric structural models and source mechanisms. Toyokuni *et al.* (2005) generalized the method for an arbitrary asymmetric structural model. Then, Toyokuni and Takenaka (2006, 2009, 2012) successively developed the scheme for an arbitrary moment-tensor point source, effective FDM grid parameters to enhance computational accuracy, attenuative structures, and the Earth's center. The computational accuracy of this scheme has been guaranteed based on comparisons with three-component seismograms at stations worldwide (Toyokuni *et al.*, 2012b).

In this work, we used the isotropic preliminary reference Earth model (PREM) (Dziewonski and Anderson, 1981) without the ocean as a structural model, and the centroid moment tensor (CMT) solution in the Harvard catalog. A source time function is a bell-shaped pulse with a width of 60 s, which is narrower than the source duration of the Sumatra earthquake, as estimated by the Harvard CMT solution (half duration, 47.3 s). However, the first peak of the source time function is well approximated by the 60 s pulse; thus, we adjusted the resulting amplitudes of synthetic seismograms by considering the source frequency contents.

Figure 10 compares the comparison of the waveforms of the particle velocity at the three stations. Because the synthetics are calculated for a spherically symmetric Earth, we focused on waveforms before the arrival of the *SKS* phase. Synthetic seismograms are also shifted with respect to the first *P* arrival. We can confirm good agreements on waveforms for all components and stations, which indicates that the observed long-period waveforms from the three sites have not been affected by the location of the installations; therefore, the

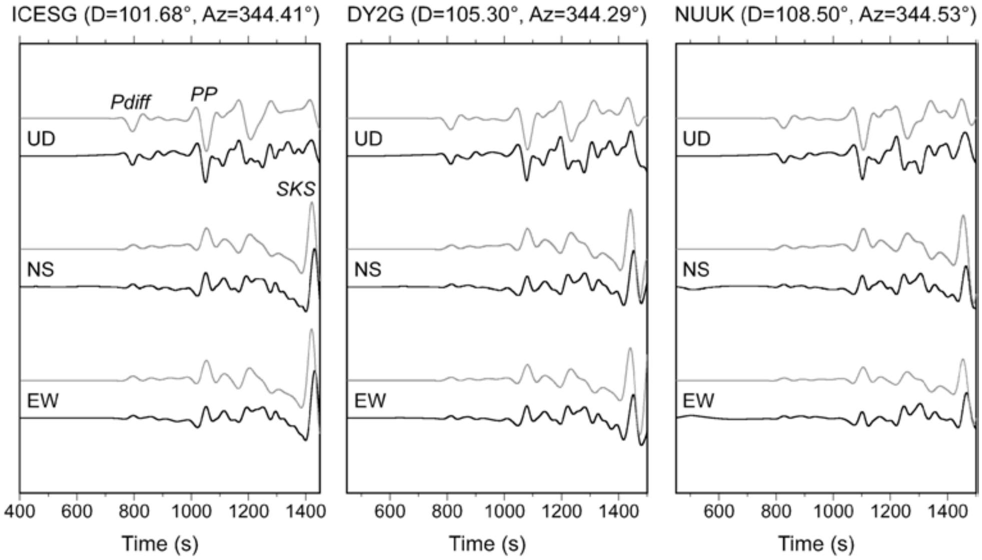

Fig. 10. Comparison of observed (black) and synthetic (gray) seismograms for the Apr. 11, 2012, Sumatra earthquake obtained at the three stations. Each panel shows the waveforms for the vertical, north—south, and east—west channels obtained at stations ICESG (left), DY2G (middle), and NUUK (right). Waveforms prior to the S*-wave arrival are plotted. All traces are band-pass filtered at 60–800 s.*

quality of the data is well controlled.

7. Concluding remarks

This paper has summarized our field activities on the GLISN project during 2011 and 2012. In 2011, the Japanese GLISN team, together with the USA team, installed the dual seismic-GPS station ICESG-GLS2 in the middle of the Greenland ice cap. In 2012, we performed maintenance at stations ICESG-GLS2, NUUK, and DY2G-GLS1. Comparisons of resulting seismograms obtained on rock (NUUK) and those obtained on ice (ICESG, DY2G) with global synthetic seismograms indicate that, at the present time, the installations on the snow surface do not cause serious noise contamination. However, during the summer season, 2012, after our field operations, substantial surface melt was recorded on the Greenland ice sheet, which caused exposure of the plastic dome covering the surface seismometer (Childs, 2012) at station DY2G-GLS1. Periodic maintenance and checks on data quality are crucial for polar seismology. In 2013, we plan to participate in maintenance operations on all three dual seismic-GPS stations: ICESG-GLS2, DY2G-GLS1, and NEEM-GLS3. We plan to continue our activities so as to obtain the highest quality data possible from the GLISN seismometer network.

Acknowledgments

The authors are grateful to an anonymous reviewer for helpful comments on an earlier draft of this paper. The Japanese GLISN team has been supported by JSPS KAKENHI 24403006.

References

Childs, D. (2012): Greenland Ice Sheet Monitoring Network (GLISN) 2012 annual field report. Washington, D.C., Incorporated Research Institutions for Seismology, 49 p.

CH2M HILL Polar Services (2013): Greenland Guide 2013. Littleton, CO, CH2M HILL Polar Services, 23 p. (online), http://www.polar.ch2m.com/Files/PDFs/GreenlandGuide2012.pdf.

Dahl-Jensen, T., Larsen, T.B., Voss, P.H. and the GLISN group (2010): Greenland ice sheet monitoring network (GLISN): a seismological approach. Geol. Surv. Den. Greenl., **20**, 55–58.

Dziewonski, A.M. and Anderson, D.L. (1981): Preliminary reference Earth model. Phys. Earth Planet In., **25**, 297–356, doi: 10.1016/0031–9201(81)90046–7.

Ekström, G., Nettles, M. and Abers, G.A. (2003): Glacial earthquakes. Science, **302**, 622–624, doi: 10.1126/science.1088057.

Ekström, G., Nettles, M. and Tsai, V.C. (2006): Seasonality and increasing frequency of Greenland glacial earthquakes. Science, **311**, 1756–1758, doi: 10.1126/science.1122112.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (2001): Climate Change 2001: the Scientific Basis. Cambridge ; New York, Cambridge University Press, x, 881 p.

Igel, H. and Weber, M. (1995): SH-wave propagation in the whole mantle using high-order finite differences. Geophys. Res. Lett., **22**, 731–734, doi: 10.1029/95GL00312.

Igel, H. and Weber, M. (1996): P-SV wave propagation in the Earth's mantle using finite differences: Application to heterogeneous lowermost mantle structure. Geophys. Res. Lett., **23**, 415–418, doi: 10.1029/96GL00422.

Toyokuni, G. and Takenaka, H. (2006): FDM computation of seismic wavefield for an axisymmetric earth with a moment tensor point source. Earth Planets Space, **58**, e29–e32.

Toyokuni, G. and Takenaka, H. (2009): ACE—A FORTRAN subroutine for analytical computation of effective grid parameters for finite-difference seismic waveform modeling with standard Earth models. Comput. Geosci., **35**, 635–643, doi: 10.1016/j.cageo.2008.05.005.

Toyokuni, G. and Takenaka, H. (2012): Accurate and efficient modeling of global seismic wave propagation for an attenuative Earth model including the center. Phys. Earth Planet In., **200–201**, 45–55, doi: 10.1016/j.pepi.2012.03.010.

Toyokuni, G., Takenaka, H., Wang, Y. and Kennett, B.L.N. (2005): Quasi-spherical approach for seismic wave modeling in a 2-D slice of a global Earth model with lateral heterogeneity. Geophys. Res. Lett., **32**, L09305, doi: 10.1029/2004GL022180.

Toyokuni, G., Takenaka, H. and Kanao, M. (2012a): Quasi-axisymmetric finite-difference method for realistic modeling of regional and global seismic wavefield—review and application—. Seismic Waves: Research and Analysis, ed. by Kanao, M. Rijeka, InTech, 85–112, doi: 10.5772/32422.

Toyokuni, G., Takenaka, H., Kanao, M., Wiens, D.A. and Nyblade, A. (2012b): Comparison of global synthetic seismograms calculated using the spherical 2.5-D finite-difference method with observed long-period waveforms including data from the intra-Antarctic region. Polar Sci., **6**, 155–164, doi: 10.1016/j.polar.2012.06.001.

Walsh, M.R. and Ueda, H.T. (1998): Structural analysis of DEW line station DYE-2, Greenland: 1983–1988. Hanover, U.S. Army Cold Regions Research & Engineering Laboratory, 23 p. (CRREL report, **98**(3)).